(Houghton, 2005). While the estimates of forest expansion and regrowth in the temperate and boreal zones appear relatively well constrained by available data and consistent across published results, the rates of tropical deforestation are uncertain and hotly debated (Table 9.2; Fearnside and Laurance, 2004). Studies based on remote sensing of forest cover report lower rates than UN-ECE/FAO (2000) and lower carbon emissions carbon (Achard *et al.*, 2004).

Recent analyses highlight the important role of other carbon flows. These flows were largely overlooked by earlier research and include carbon export through river systems (Raymond and Cole, 2003), volcanic activity and other geological processes (Richey *et al.*, 2002), transfers of material in and out of products pool (Pacala *et al.*, 2001), and uptake in freshwater ecosystems (Janssens *et al.*, 2003).

Attribution of estimated carbon sink in forests to the short- and long-term effects of the historic land-use change and shifting natural disturbance patterns on one hand, and to the effects of N and CO_2 fertilization and climate change on the other, remains problematic (Houghton, 2003b). For the USA, for example, the fraction of carbon sink attributable to changes in land-use and land management might be as high as 98% (Caspersen *et al.*, 2000), or as low as 40% (Schimel *et al.*, 2001). Forest expansion and regrowth and associated carbon sinks were reported in many regions (Table 9.2; Figure 9.2). The expanding tree cover in South Western USA is attributed to the long-term effects of fire control but the gain in carbon storage was smaller than previously thought. The lack of consensus on factors that control the carbon balance is an obstacle to development of effective mitigations strategies.

Large year-to-year and decade scale variation of regional carbon sinks (Rodenbeck *et al.*, 2003) make it difficult to define distinct trends. The variation reflects the effects of climatic variability, both as a direct impact on vegetation and through the effects of wild fires and other natural disturbances. There are indications that higher temperatures in boreal regions will increase fire frequency; possible drying of the Amazon basin would increase fire frequency there as well (Cox *et al.*, 2004). Global emissions from fires in the 1997/98 El Nino year are estimated at 7,700 $MtCO_2$/yr, 90% from tropics (Werf *et al.*, 2004).

The picture emerging from Table 9.2 is complex because available estimates differ in the land-use types included and in the use of gross fluxes versus net carbon balance, among other variables. This makes it impossible to set a widely accepted baseline for the forestry sector globally. Thus, we had to rely on the baselines used in each regional study separately (Section 9.4.3.1), or used in each global study (Section 9.4.3.3). However, this approach creates large uncertainty in assessing the overall mitigation potential in the forest sector. Baseline CO_2 emissions from land-use change and forestry in 2030 are the same as or slightly lower than in 2000 (see Chapter 3, Figure 3.10).

9.4 Assessment of mitigation options

In this section, a conceptual framework for the assessment of mitigation options is introduced and specific options are briefly described. Literature results are summarized and compared for regional bottom-up approaches, global forest sector models, and global top-down integrated model approaches. The assessment is limited to CO_2 balances and economic costs of the various mitigation options. Broader issues including biodiversity, sustainable development, and interactions with adaptation strategies are discussed in subsequent sections.

9.4.1 Conceptual introduction

Terrestrial carbon dynamics are characterized by long periods of small rates of carbon uptake, interrupted by short periods of

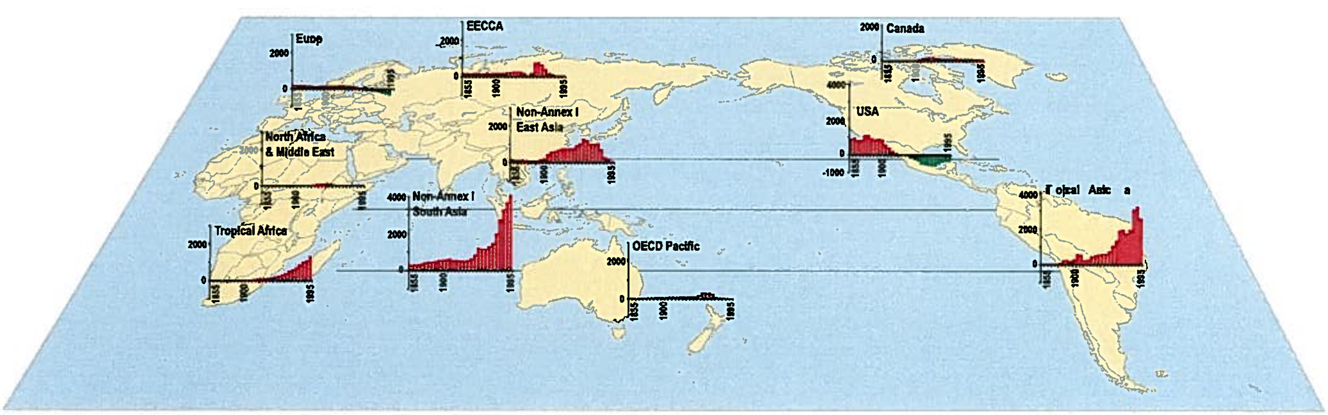

Figure 9.2: *Historical forest carbon balance ($MtCO_2$) per region, 1855-2000.*

Notes: green = sink. EECCA=Countries of Eastern Europe, the Caucasus and Central Asia. Data averaged per 5-year period, year marks starting year of period.
Source: Houghton, 2003b.

Table 9.2: *Selected estimates of carbon exchange of forests and other terrestrial vegetation with the atmosphere (in MtCO2/yr)*

Regions	Annual carbon flux based on international statistics	Annual carbon flux during 1990s	
	UN-ECE, 2000	Based on inversion of atmospheric transport models	Based on land observations
	MtCO$_2$/yr		
OECD North America		1,833 ± 2,200[9]	0 ÷ 1,100[5]
Separately: Canada USA	340 610	2,090 ± 3,337[2]	293 ± 733[1]
OECD Pacific	224		0±733[1]
Europe	316	495 ± 752[6]	0 ± 733[1] 513[11]
Countries in Transition	1,726	3,777 ± 3,447[2]	1,100 ± 2,933[9] 1,181 ÷ -1,588[7]
Separately: Russia	1,572	4,767 ± 2,933[9]	1,907± 469[8]
Northern Africa		623 ± 3,593[2]	
Sub-Saharan Africa			-576 ±235[3] -440 ± 110[4] -1,283 ± 733[1]
Caribbean, Central and South America		-2,310	-1,617 ± 972[3] -1,577 ± 733[4] -2,750 ± 1,100[1]
Separately: Brazil			± 733[12]
Developing countries of South and East Asia and Middle East		-2,493 ± 2,713[2]	-3,997 ± 1,833[1] -1,734 ± 550[3] -1,283 ± 550[4]
Separately: China		2,273 ± 2,420[2]	- 110 ± 733[1] 128 ± 95[13] 249[14]
Global total		4,767 ± 5,500[9] 2,567 ± 2,933[10] 4,913[2] 9516[17]	-7,993 ± 2,933[1] -3,300 ÷ 7,700[5] -4,000[15] -5,800 [16] -8485[18]
Annex I (excluding Russia)			1300[19]

Notes: Positive values represent carbon sink, negative values represent source. Sign ÷ indicates a range of values; sign ± indicates error term.
Because of differences in methods and scope of studies (see footnotes), values from different publications are not directly comparable. They represent a sample of reported results.
1 Houghton 2003a (flux from changes in land use and land management based on land inventories); 2 Gurney et al., 2002 (inversion of atmospheric transport models, estimate for Countries in Transition applies to Europe and boreal Asia; estimate for China applies to temperate Asia); 3 Achard et al., 2004 (estimates based on remote sensing for tropical regions only); 4 DeFries, 2002 (estimates based on remote sensing for tropical regions only); 5 Potter et al., 2003 (NEP estimates based on remote sensing for 1982-1998 and ecosystem modelling, the range reflects inter-annual variability); 6 Janssens et al., 2003 (combined use of inversion and land observations; includes forest, agricultural lands and peatlands between Atlantic Ocean and Ural Mountains, excludes Turkey and Mediterranean isles); 7 Shvidenko and Nilson, 2003 (forests only, range represents difference in calculation methods); 8 Nilsson et al., 2003 (includes all vegetation); 9 Ciais et al., 2000 (inversion of atmospheric transport models, estimate for Russia applies to Siberia only); 10 Plattner et al., 2002 (revised estimate for 1980's is 400±700); 11Nabuurs et al., 2003 (forests only); 12 Houghton et al., 2000 (Brazilian Amazon only, losses from deforestation are offset by regrowth and carbon sink in undisturbed forests); 13 Fang et al., 2005; 14 Pan et al., 2004, 15 FAO, 2006a (global net biomass loss resulting from deforestation and regrowth); 16 Denman *et al.*,2007 (estimate of biomass loss from deforestation), 17 Denman et al.,2007 (Residual terrestrial carbon sink), 18 EDGAR database for agriculture and forestry (see Chapter 1, Figure 1.3a/b (Olivier et al., 2005)). These include emissions from bog fires and delayed emissions from soils after land- use change, 19 (Olivier et al., 2005).

rapid and large carbon releases during disturbances or harvest. Depending on the stage of stand[1] development, individual stands are either carbon sources or carbon sinks (1m^3 of wood stores ~ 0.92 tCO_2)[2]. For most immature and mature stages of stand development, stands are carbon sinks. At very old ages, ecosystem carbon will either decrease or continue to increase

1 In this chapter, 'stand' refers to an area of trees of similar characteristics (e.g., species, age, stand structure or management regime) while 'forest' refers to a larger estate comprising many stands.
2 Assuming a specific wood density of 0.5g dry matter/cm3 and a carbon content of 0.5g C/g dry matter.

slowly with accumulations mostly in dead organic matter and soil carbon pools. In the years following major disturbances, the losses from decay of residual dead organic matter exceed the carbon uptake by regrowth. While individual stands in a forest may be either sources or sinks, the forest carbon balance is determined by the sum of the net balance of all stands. The theoretical maximum carbon storage (saturation) in a forested landscape is attained when all stands are in old-growth state, but this rarely occurs as natural or human disturbances maintain stands of various ages within the forest.

The design of a forest sector mitigation portfolio should consider the trade-offs between increasing forest ecosystem carbon stocks and increasing the sustainable rate of harvest and transfer of carbon to meet human needs (Figure 9.3). The selection of forest sector mitigation strategies should minimize net GHG emissions throughout the forest sector and other sectors affected by these mitigation activities. For example, stopping all forest harvest would increase forest carbon stocks, but would reduce the amount of timber and fibre available to meet societal needs. Other energy-intensive materials, such as concrete, aluminium, steel, and plastics, would be required to replace wood products, resulting in higher GHG emissions (Gustavsson *et al.,* 2006). Afforestation may affect the net GHG balance in other sectors, if for example, forest expansion reduces agricultural land area and leads to farming practices with higher emissions (e.g., more fertilizer use), conversion of land for cropland expansion elsewhere, or increased imports of agricultural products (McCarl and Schneider, 2001). The choice of system boundaries and time horizons affects the ranking of mitigation activities (Figure 9.3).

Forest mitigation strategies should be assessed within the framework of sustainable forest management, and with consideration of the climate impacts of changes to other processes such as albedo and the hydrological cycle (Marland *et al.*, 2003). At present, however, few studies provide such comprehensive assessment.

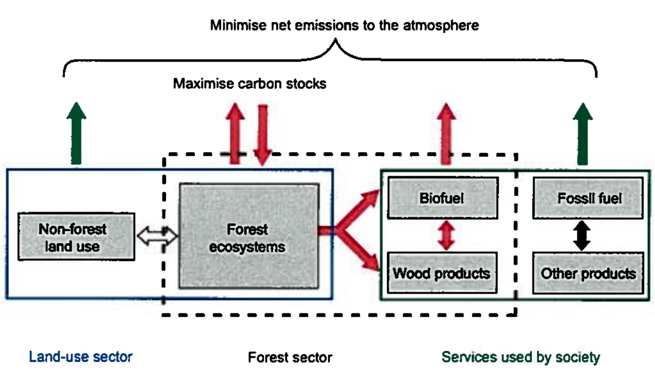

Figure 9.3: *Forest sector mitigation strategies need to be assessed with regard to their impacts on carbon storage in forest ecosystems on sustainable harvest rates and on net GHG emissions across all sectors.*

For the purpose of this discussion, the options available to reduce emissions by sources and/or to increase removals by sinks in the forest sector are grouped into four general categories:
- maintaining or increasing the forest area through reduction of deforestation and degradation and through afforestation/ reforestation;
- maintaining or increasing the stand-level carbon density (tonnes of carbon per ha) through the reduction of forest degradation and through planting, site preparation, tree improvement, fertilization, uneven-aged stand management, or other appropriate silviculture techniques;
- maintaining or increasing the landscape-level carbon density using forest conservation, longer forest rotations, fire management, and protection against insects;
- increasing off-site carbon stocks in wood products and enhancing product and fuel substitution using forest-derived biomass to substitute products with high fossil fuel requirements, and increasing the use of biomass-derived energy to substitute fossil fuels.

Each mitigation activity has a characteristic time sequence of actions, carbon benefits and costs (Figure 9.4). Relative to a baseline, the largest short-term gains are always achieved through mitigation activities aimed at emission avoidance (e.g., reduced deforestation or degradation, fire protection, and slash burning). But once an emission has been avoided, carbon stocks on that forest will merely be maintained or increased slightly. In contrast, the benefits from afforestation accumulate over years to decades but require up-front action and expenses. Most forest management activities aimed at enhancing sinks require up-front investments. The duration and magnitude of their carbon benefits differ by region, type of action and initial condition of the forest. In the long term, sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual yield of timber, fibre, or energy from the forest, will generate the largest sustained mitigation benefit.

Reduction in fossil fuel use in forest management activities, forest nursery operations, transportation and industrial production provides additional opportunities similar to those in other sectors, but are not discussed here (e.g., see Chapter 5, Transportation). The options available in agro-forestry systems are conceptually similar to those in other parts of the forest sector and in the agricultural sector (e.g., non-CO_2 GHG emission management). Mitigation using urban forestry includes increasing the carbon density in settlements, but indirect effects must also be evaluated, such as reducing heating and cooling energy use in houses and office buildings, and changing the albedo of paved parking lots and roads.

9.4.2 Description of mitigation measures

Each of the mitigation activities is briefly described. The development of a portfolio of forest mitigation activities requires

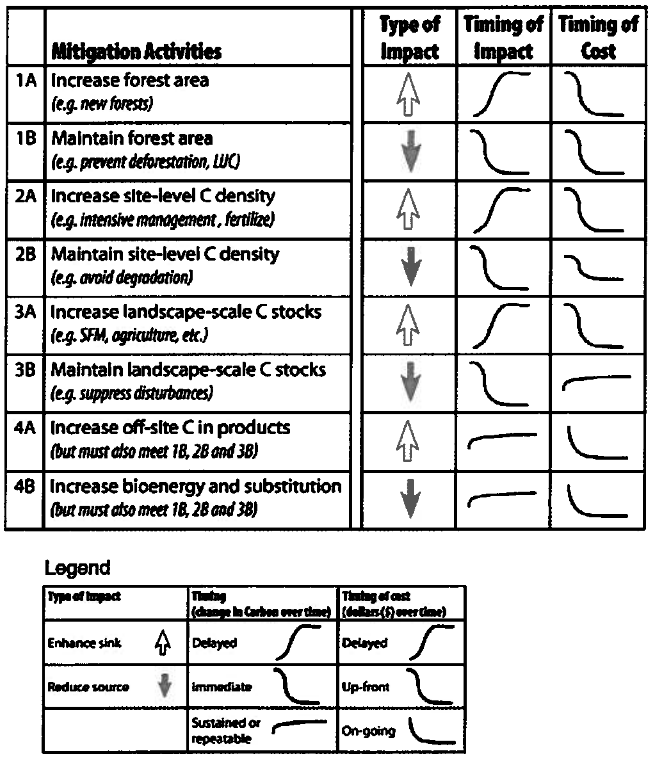

Figure 9.4: *Generalized summary of forest sector options and type and timing of effects on carbon stocks and the timing of costs* [3]

an understanding of the magnitude and temporal dynamics of the carbon benefits and the associated costs.

9.4.2.1 *Maintaining or increasing forest area: reducing deforestation and degradation*

Deforestation - human-induced conversion of forest to non-forest land uses - is typically associated with large immediate reductions in forest carbon stock, through land clearing. Forest degradation - reduction in forest biomass through non-sustainable harvest or land-use practices - can also result in substantial reductions of forest carbon stocks from selective logging, fire and other anthropogenic disturbances, and fuelwood collection (Asner *et al.*, 2005).

In some circumstances, deforestation and degradation can be delayed or reduced through complete protection of forests (Soares-Filho *et al.*, 2006), sustainable forest management policies and practices, or by providing economic returns from non-timber forest products and forest uses not involving tree removal (e.g., tourism). Protecting forest from all harvest typically results in maintained or increased forest carbon stocks, but also reduces the wood and land supply to meet other societal needs.

Reduced deforestation and degradation is the forest mitigation option with the largest and most immediate carbon stock impact in the short term per ha and per year globally (see Section 9.2 and global mitigation assessments below), because large carbon stocks (about 350-900 tCO_2/ha) are not emitted when deforestation is prevented. The mitigation costs of reduced deforestation depend on the cause of deforestation (timber or fuelwood extraction, conversion to agriculture, settlement, or infrastructure), the associated returns from the non-forest land use, the returns from potential alternative forest uses, and on any compensation paid to the individual or institutional landowner to change land-use practices. These costs vary by country and region (Sathaye *et al.*, 2007), as discussed below.

9.4.2.2 *Maintaining or increasing forest area: afforestation/reforestation*

Afforestation and reforestation are the direct human-induced conversion of non-forest to forest land through planting, seeding, and/or the human-induced promotion of natural seed sources. The two terms are distinguished by how long the non-forest condition has prevailed. For the remainder of this chapter, afforestation is used to imply either afforestation or reforestation. To date, carbon sequestration has rarely been the primary driver of afforestation, but future changes in carbon valuation could result in large increases in the rates of afforestation (US EPA, 2005).

Afforestation typically leads to increases in biomass and dead organic matter carbon pools, and to a lesser extent, in soil carbon pools, whose small, slow increases are often hard to detect within the uncertainty ranges (Paul *et al.*, 2003). Biomass clearing and site preparation prior to afforestation may lead to short-term carbon losses on that site. On sites with low initial soil carbon stocks (e.g., after prolonged cultivation), afforestation can yield considerable soil carbon accumulation rates (e.g., Post and Kwon (2000) report rates of 1 to 1.5 t CO_2/yr). Conversely, on sites with high initial soil carbon stocks, (e.g., some grassland ecosystems) soil carbon stocks can decline following afforestation (e.g., Tate *et al.* (2005) report that in the whole of New Zealand soil carbon losses amount up to 2.2 $MtCO_2$/yr after afforestation). Once harvesting of afforested land commences, forest biomass carbon is transferred into wood products that store carbon for years to many decades. Accumulation of carbon in biomass after afforestation varies greatly by tree species and site, and ranges globally between 1 and 35 t CO_2/ha.yr (Richards and Stokes, 2004).

Afforestation costs vary by land type and region and are affected by the costs of available land, site preparation, and labour. The cost of forest mitigation projects rises significantly

3 We thank Mike Apps for a draft of this figure.

when opportunity costs of land are taken into account (VanKooten *et al.*, 2004). A major economic constraint to afforestation is the high initial investment to establish new stands coupled with the several-decade delay until afforested areas generate revenue. The non-carbon benefits of afforestation, such as reduction in erosion or non-consumptive use of forests, however, can more than off-set afforestation cost (Richards and Stokes, 2004).

9.4.2.3 Forest management to increase stand- and landscape-level carbon density

Forest management activities to increase stand-level forest carbon stocks include harvest systems that maintain partial forest cover, minimize losses of dead organic matter (including slash) or soil carbon by reducing soil erosion, and by avoiding slash burning and other high-emission activities. Planting after harvest or natural disturbances accelerates tree growth and reduces carbon losses relative to natural regeneration. Economic considerations are typically the main constraint, because retaining additional carbon on site delays revenues from harvest. The potential benefits of carbon sequestration can be diminished where increased use of fertilizer causes greater N_2O emissions. Drainage of forest soils, and specifically of peatlands, may lead to substantial carbon loss due to enhanced respiration (Ikkonen *et al.,* 2001). Moderate drainage, however, can lead to increased peat carbon accumulation (Minkkinen *et al.,* 2002).

Landscape-level carbon stock changes are the sum of stand-level changes, and the impacts of forest management on carbon stocks ultimately need to be evaluated at landscape level. Increasing harvest rotation lengths will increase some carbon pools (e.g., tree boles) and decrease others (e.g., harvested wood products (Kurz *et al.*, 1998).

9.4.2.4 Increasing off-site carbon stocks in wood products and enhancing product and fuel substitution

Wood products derived from sustainably managed forests address the issue of saturation of forest carbon stocks. The annual harvest can be set equal to or below the annual forest increment, thus allowing forest carbon stocks to be maintained or to increase while providing an annual carbon flow to meet society's needs of fibre, timber and energy. The duration of carbon storage in wood products ranges from days (biofuels) to centuries (e.g., houses and furniture). Large accumulations of wood products have occurred in landfills (Micales and Skog, 1997). When used to displace fossil fuels, woodfuels can provide sustained carbon benefits, and constitute a large mitigation option (see Box 9.2).

Wood products can displace more fossil-fuel intensive construction materials such as concrete, steel, aluminium, and plastics, which can result in significant emission reductions (Petersen and Solberg, 2002). Research from Sweden and Finland suggests that constructing apartment buildings with wooden frames instead of concrete frames reduces lifecycle net carbon emissions by 110 to 470 kg CO_2 per square metre of floor area (Gustavsson and Sathre, 2006). The mitigation benefit is greater if wood is first used to replace concrete building material and then after disposal, as biofuel.

9.4.3 Global assessments

For quantification of the economic potential of future mitigation by forests, three approaches are presented in current literature. These are: a) regional bottom-up assessments per country or continent; b) global forest sector models; and c) global multi-sectoral models. An overview of studies for these approaches is presented in Section 9.4.3. The final integrated global conclusion and regional comparison is given in Section 9.4.4. Supply of forest biomass for bio-energy is given in Box 9.2 and incorporated in Section 11.3.1.4, within the energy sector's mitigation potential. For comments on the baselines, see Section 9.3.

9.4.3.1 Regional bottom-up assessments

Regional assessments comprise a variety of model results. On the one hand, these assessments are able to take into account the detailed regional specific constraints (in terms of ecological constraints, but also in terms of land owner behaviour and institutional frame).On the other hand, they also vary in assumptions, type of potential addressed, options taken into account, econometrics applied (if any), and the adoption of baselines. Thus, these assessments may have strengths, but when comparing and summing up, they have weaknesses as well. Some of these assessments, by taking into account institutional barriers, are close to a market potential.

Tropics

The available studies about mitigation options differ widely in basic assumptions regarding carbon accounting, costs, land areas, baselines, and other major parameters. The type of mitigation options considered and the time frame of the study affect the total mitigation potential estimated for the tropics. A thorough comparative analysis is, therefore, very difficult. More detailed estimates of economic or market potential for mitigation options by region or country are needed to enable policy makers to make realistic estimates of mitigation potential under various policy, carbon price, and mitigation program eligibility rule scenarios. Examples to build on include Benitez-Ponce *et al.* (2007) and Waterloo *et al.* (2003), highlighting the large potential by avoiding deforestation and enhancing afforestation and reforestation, including bio-energy.

Reducing deforestation

Assumptions of future deforestation rates are key factors in estimates of GHG emissions from forest lands and of mitigation benefits, and vary significantly across studies. In all the studies,